

# Exploration of sea quark effects in two-flavor QCD with the $O(a)$ -improved Wilson quark action\*

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We explore sea quark effects in the light hadron mass spectrum in a simulation of two-flavor QCD using the nonperturbatively  $O(a)$ -improved Wilson fermion action. In order to identify finite-size effects, light meson masses are measured on  $12^3 \times 48$ ,  $16^3 \times 48$  and  $20^3 \times 48$  lattices with  $a \sim 0.1$  fm. On the largest lattice, where the finite-size effect is negligible, we find a significant increase of the strange vector meson mass compared to the quenched approximation. We also investigate the quark mass dependence of pseudoscalar meson masses and decay constants and test the consistency with (partially quenched) chiral perturbation theory.

## 1. Introduction

While encouraging results are being accumulated on the effect of dynamical quarks in the light hadron spectrum [1], further effort is needed to establish its presence and magnitude with precision. In this study we explore the sea quark effects in two-flavor QCD with the  $O(a)$ -improved Wilson fermion. In particular, we analyze the strange vector meson masses in detail, for which quenched QCD fails to reproduce the experimental values [2]. Since the hadron spectrum may be distorted by a finite box size especially for light sea quark masses, we carry out simulations with three volumes in order to identify the finite size effect.

Another point of our study is a test of chiral perturbation theory for pseudoscalar meson masses and decay constants. The appearance of the chiral logarithm in the quark mass, which depends only on the number of active flavors, provides a definite test of the sea quark effect.

## 2. Two-flavor QCD simulations

The JLQCD collaboration has been performing a two-flavor QCD simulation with the standard glue and the  $O(a)$ -improved Wilson quark actions at  $\beta = 5.2$  [3]. The improvement coefficient  $c_{\text{sw}}$  is determined nonperturbatively [4] as  $c_{\text{sw}}=2.02$ , which we confirmed in the course of this study. We choose five values of the hopping parameter  $\kappa$  ( $\kappa = 0.1340, 0.1343, 0.1346, 0.1350$ , and  $0.1355$ ) to cover the range  $m_{PS}/m_V = 0.8\text{--}0.6$ . The effective lattice spacing determined through the static quark potential changes from  $a^{-1} = 1.6$  GeV to 2.0 GeV as the sea quark mass decreases.

In order to detect finite size effects we perform simulations on three lattices  $12^3 \times 48$ ,  $16^3 \times 48$ , and  $20^3 \times 48$ . The simulations run through 3000 HMC trajectories for each  $\kappa$ . An additional 3000 trajectories is performed with a better preconditioning [5] for the  $20^3$  lattice. Some earlier results on the  $16^3$  lattice were already presented at the last lattice conference [3].

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\*Talk presented by S. Hashimoto

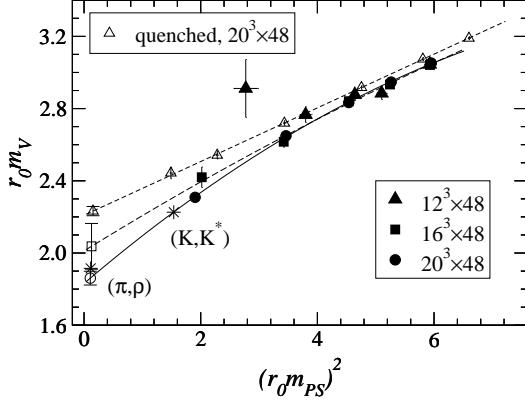


Figure 1. Degenerate vector meson masses in quenched and two-flavor QCD. Stars represent the physical points with  $r_0=0.49$  fm.

### 3. Vector meson mass

We plot results for degenerate pseudoscalar and vector meson masses on three lattice volumes in Figure 1 together with quenched data. Finite-size effects badly affect the masses on the smallest volume ( $12^3$ ) except for the heaviest point. The next largest lattice ( $16^3$ ) suffers less, but we still find significant difference from the largest lattice ( $20^3$ ) at the lightest data point, which corresponds to  $m_{PS}/m_V \simeq 0.6$ . The effect is about 3% ( $1.9 \sigma$ ) for pseudoscalar and 5% ( $2.0 \sigma$ ) for vector mesons. Our observation implies that the effective lattice extent (at finite sea quark mass) should be kept larger than 2 fm in order to avoid finite size effects in (lowest lying) light meson masses for  $m_{PS}/m_V \geq 0.6-0.7$ . A similar study indicates that the corresponding spatial extent for baryons is at least 2.5 fm.

In Figure 1 we normalize masses by  $r_0$  to absorb the change of effective lattice spacing for different sea quark masses. We find a significant curvature for the  $20^3$  lattice, in contrast to the quenched case for which no signal of curvature is observed. By a quadratic fit to reach the chiral limit we obtain  $r_0 m_\rho = 1.86(4)$ , consistent with the phenomenological value  $r_0 = 0.49$  fm.

Strange meson masses are obtained by measuring non-degenerate mesons for which sea and valence quark masses are different. Taking the chi-

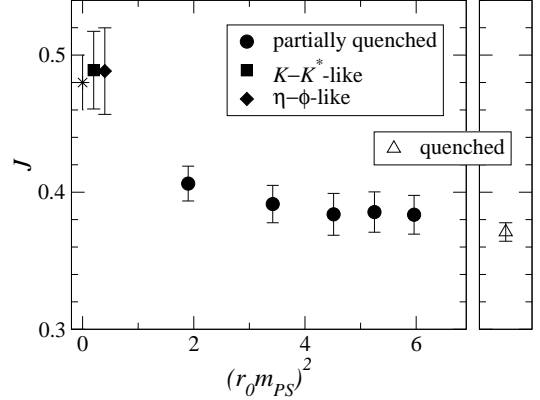


Figure 2.  $J$  parameter as a function of sea quark mass. A quenched result is in the right panel.

ral limit for sea quark we obtain  $K-K^*$ -like and  $\eta-\phi$ -like combinations. Using the  $K$  meson mass as input for the strange quark mass we obtain  $m_{K^*}/m_\rho = 1.15(1)$  and  $m_\phi/m_\rho = 1.29(2)$ . These results are significantly higher than the quenched results and closer to the experimental values.

The  $J$  parameter [6] may be calculated for a fixed sea quark mass varying valence quark masses. The results are plotted in Figure 2 as a function of  $(r_0 m_{PS})^2$ . Compared to the quenched estimate, the two-flavor value of  $J$  is slightly higher and shows a trend of increase toward the chiral limit. The  $J$  parameter can also be constructed from the  $K-K^*$ -like and  $\eta-\phi$ -like combinations. These are consistent with the phenomenological estimate as shown in Figure 2.

### 4. Test of chiral perturbation theory

In order to obtain a controlled chiral limit of the lattice data, chiral perturbation theory (ChPT) may be used as a guide. Prior to adopting this strategy, it is worth testing if lattice data are consistent with the chiral behavior predicted by ChPT, especially the chiral logarithms.

For  $N_f$  flavors of degenerate quarks with a mass  $m_S$ , the pseudoscalar meson mass  $M_{SS}$  to one-loop order of ChPT is [7] given by

$$\frac{M_{SS}^2}{2B_0 m_S} = 1 + \frac{1}{N_f} y_{SS} \ln y_{SS} + y_{SS} [(2\alpha_8 - \alpha_5) + N_f (2\alpha_6 - \alpha_4)] \quad (1)$$

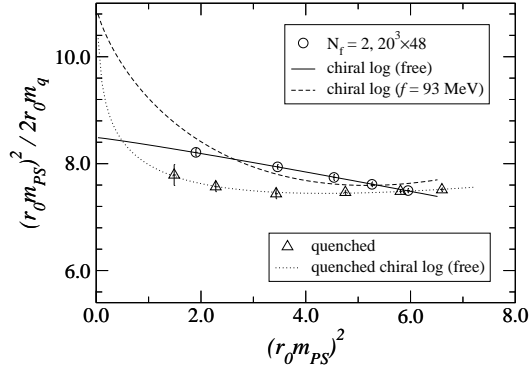


Figure 3. Test of the ChPT formula for the pseudoscalar meson mass.

with  $y_{SS} = 2B_0 m_S / (4\pi f)^2$ . While the low energy constants  $\alpha_i$  are unknown parameters, the chiral log term  $y_{SS} \ln y_{SS}$  appears with a definite coefficient depending only on the number of flavors.

Figure 3 shows the unquenched and quenched results for  $M_{SS}^2/2m_S$ . While there is a visible difference between the two sets of results, the two-flavor data do not show the curvature expected from the chiral logarithm shown by a dashed curve. The situation is the same for the chiral behavior of the pseudoscalar decay constant.

We also perform a test for non-degenerate mesons using the partially quenched ChPT (PQChPT) [8] by considering a ratio for which the low energy constants cancel

$$\left( \frac{M_{VS}^2}{m_V + m_S} \right)^2 = 1 + \frac{y_{SS}}{N_f} t, \quad (2)$$

where  $t \equiv \ln \frac{y_{VV}}{y_{SS}} + 1 - \frac{y_{VV}}{y_{SS}}$ . The subscript  $V$  denotes a valence quark whose mass may be different from the sea quark mass. In our preliminary results we find that the coefficient of  $t$ , the chiral logarithm term, is much smaller than expected. A similar result is also observed for the decay constants.

A possible reason for the deficit of the chiral logarithm is that the sea quark mass in our simulations is still too large to be described by ChPT. In fact, if one introduces a singlet meson  $\eta'$  into PQChPT [9] the chiral logarithm is substantially suppressed unless  $M_{SS}^2$  is much smaller

than  $m_0^2/3$ , the additional mass for the singlet meson. In our simulation, however,  $M_{SS}^2/(m_0^2/3)$  is  $O(1)$ .

## 5. Conclusions

In the two-flavor QCD simulation we find an evidence of the sea quark effect in the strange vector meson masses. A large enough lattice volume, at least  $(2 \text{ fm})^3$ , is necessary to identify the sea quark effect without suffering from the finite size effect. On the other hand, the lattice data for the pseudoscalar meson masses and decay constants fail to reproduce the chiral logarithms, suggesting that the sea quark mass corresponding to  $m_{PS}/m_V \geq 0.6$  is still too large to be described by ChPT. We are currently accumulating further statistics to confirm these findings.

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